Industrial Advanced Turbine Systems Program Overview

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Introduction

This document contains the annual ATS report required of Solar Turbines Incorporated by the contracts listed in Footnote 1 below. Since our 1996 report to the Department of Energy, Solar has completed its design of a 4.3 megawatt, 40.5 percent efficient (80° F day) industrial gas turbine system, which has been named the Mercury 50™. This report consists of the Mercury 50 product description, and includes a discussion of the technologies that have been developed that will lead to a commercially viable industrial product.

Mercury 50 Design

While technology improvements can offer significant benefits, industrial gas turbine users have often shied away from new technologies, concerned about potential impacts to overall reliability. Rather, they prefer a sensible balance between the demonstrated benefits of key technologies and the high reliability requirements demanded by their businesses. Solar's technical approach to ATS emphasizes the use of system-level design solutions that take advantage of a wide variety of demonstrated technological advances, each providing sufficient margin to assure the superior durability and availability that are required by industrial gas turbine users.

A combination of innovative primary and backup design solutions have been carefully blended (Table 1) to offer maximum cycle efficiency and emissions reductions with minimal risk, as adequate design margin is maintained within each selected technology.

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Technology	Benefit	Delta Thermal Efficiency - %
Rotor Sealing/Cooling	0.3% Less Cooling Air	0.2
Blade Screw Cooling	0.4% Less Cooling Air	0.2
Abradable Tip Seals	0.6% More Turbine Efficiency	0.4
Udimet 720 Disk	0.8% Less Cooling Air	0.5
CMSX-10 Blades	0.6% Less Cooling Air	0.3
Subtotal Engine Baseline		1.6

Table 1. Technologies used for ATS

Primary Surface Recuperator

Recuperated cycles have been applied to gas turbines in the past with varied degrees of success. In general, bulky shell-and-tube or plate-fin heat exchangers were added on to existing engines using somewhat elaborate and often cumbersome piping and support arrangements with little or no attempt made to optimize the cycle. The result was a lukewarm performance improvement accompanied by poor thermal transient response, thermal cracking and other mechanical performance problems within the recuperator that often failed to meet customer expectations. Yet when an engine such as Solar's Mercury 50 is designed to accommodate the recuperator from the start, significant gains can be realized without incurring the mechanical performance issues that have occurred in the past.

At the heart of the Mercury 50 lies Solar's proven Primary Surface Recuperator (PSR). The construction is rugged and the modular nature of the design gives it superior flexibility to handle thermal stresses. Air cells (Figure 1) are constructed from 0.004 inch thick sheets of type 347 stainless steel (SS 347) folded into a corrugated pattern. This folded shape maximizes the primary surface area that is in direct contact with exhaust gas on one side and compressor discharge air on the other.

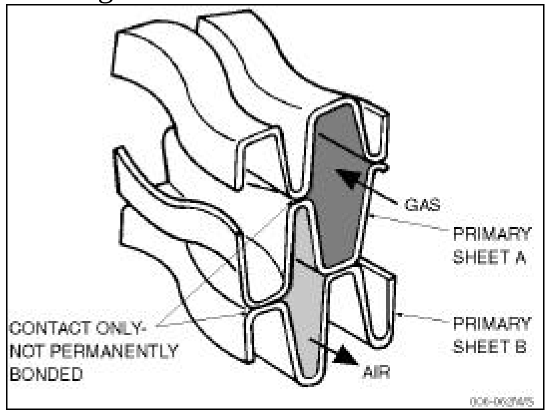


Figure 1 – PSR Air Cell Structure

Pairs of these sheets are welded together around the perimeter to form air cells (Figure 2). These air cells are the basic

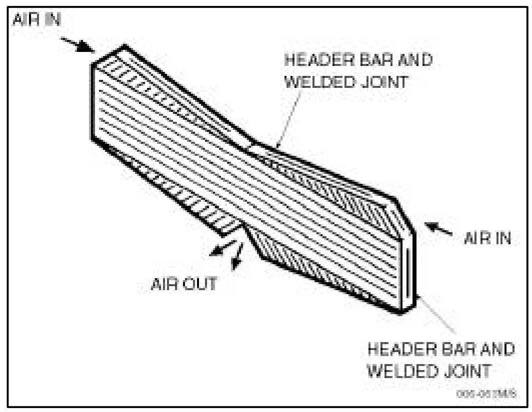


Figure 2 – PSR Air Cells

building block of the PSR and are manufactured in Solar's recently completed automated production facility in Channelview Texas. There are no internal welds or joints within the air cell. Groups of these cells are sandwiched together (Figure 3) via an arrangement of clamping bars and are welded to intake and discharge headers to form the recuperator itself.

Developed by Caterpillar engineers in the early 1970s, the PSR has undergone numerous refinements and has been successfully applied to a variety of gas turbines over the years. To date, Solar PSRs have accumulated well in excess of 2.5 million operating hours

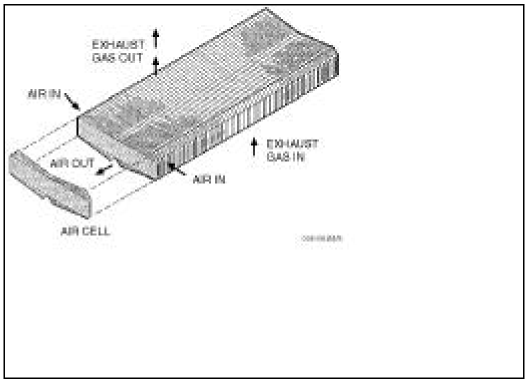


Figure 3 – Recuperator Construction

with few of the incipient problems typical of alternative recuperator technologies. In contrast, the nature of the PSR presents several major advantages over plate-fin and shell-and-tube heat exchangers (Table 2). The Solar PSR is inherently resistant to low-cycle fatigue failure. Clamping the cells rather than rigidly welding them to one another allows the assembly to flex freely to relieve stresses, rather than concentrating stresses at the weld locations. Similarly, high-cycle fatigue has not been a problem for the PSR due to the inherent damping characteristics of the clamped design: the stacking of cells presents multiple friction interfaces for energy absorption. This characteristic also provides excellent exhaust sound suppression, eliminating the need for an additional silencing device and its associated pressure drop.

Feature	Technology			
	PSR	Compact Plate-Fin	Traditional Plate-Fin	Shell and Tube
Size (l x w x h), m ft	4.7 x 3.35 x 0.3 15.6 x 11 x 1	3.65 x 3 x 1.2 12 x 10 x 4	3.35 x 4.5 x 2.4 11 x 14.8 x 8	2.4 (dia) x 12.2 (h) 8 (dia) x 40 (h)
Weight, kg lb_m	8554 18,820	11,818 26,000	56,818 125,000	77,272 170,000
Volume, m^3 ft^3	4.84 171	13.6 480	36.7 1298	57 2011
Effectiveness, %	88 to 91	87	79	84
Installation Flexibility	High	High	Moderate	Low
Thermal Mass	Low	Medium	Medium	High
Warm-Up / Cool-Down Cycle	None	Yes	Yes	Yes

Comparison based on 14,000-hp turbine

Table 2 - Various Recuperator Technologies

PSRs are significantly smaller and lighter than competing technologies (Figure 4), have superior performance, improved reliability and can easily accommodate the thermal transients associated with startups, shutdowns and full-load transients during turbine operation. The PSR provides the high effectiveness (>90 percent), moderate pressure drop and long life demanded by industrial turbine applications.

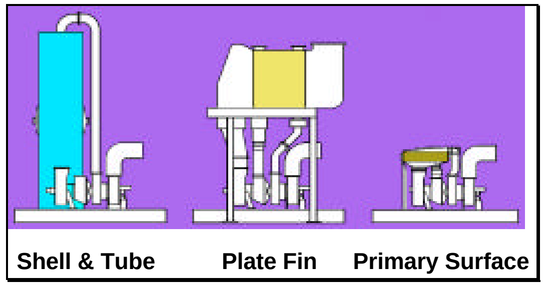


Figure 4 – Recuperator Comparison

Advanced Component Efficiency (ACE) Compressor

The Mercury 50 engine design has incorporated Solar's latest generation of compressors, the ACE compressor (Figure 5). Working in concert with Dr. John Adamczyk from NASA's Lewis Research Center in Cleveland Ohio, these highly efficient, rugged compressors have brought the latest state-of-the-art aerodynamic design codes and modeling techniques to the design of industrial turbine compressors. These techniques were first applied during the redesign of the Mars® T15000 compressor in 1993. The ACE compressor design uses 3-dimensional wide chord airfoils that are lightly loaded, resulting in a 40% reduction in the number of airfoils for a given pressure rise.

Validation of this design was completed in July 1997 at the U.S. Air Force's Compressor Research Facility at Wright-Patterson Air Force Base in Dayton Ohio. During this testing, compressor

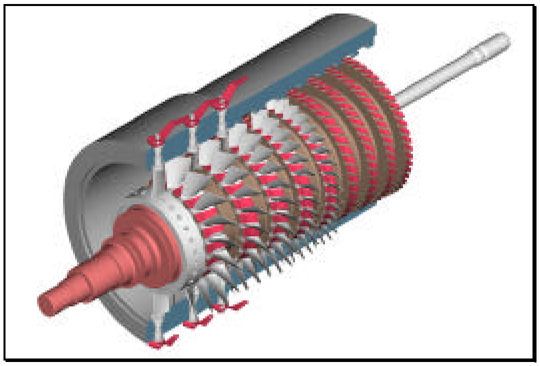


Figure 5 - Mercury 50 ACE Compressor

performance was fully mapped and compared to the design goals as well as that of Solar's current compressors. The results validated the ACE design goals and yielded an overall efficiency improvement that is more than 2 points better than the compressors in use on Solar's current line of gas turbines. ACE technology will form the backbone of all future compressor design modifications.

The single-shaft Mercury 50 design uses a 10-stage version of this compressor for a 9.1:1 pressure ratio. A variable inlet guide vane (IGV) is followed by two stages of variable guide vanes (VGV) that are ganged together and controlled as a unit for optimum compressor control across the operating load range.

Turbine

The design of the Mercury 50 turbine (Figure 6) incorporates several advanced features that are new to Solar's turbines. This two-stage design was chosen for its inherent cost advantages and is characterized by a turbine rotor inlet temperature (TRIT) of 2125°F and a highly loaded, fully cooled first-stage turbine. The second stage incorporates cooled vanes and uncooled, shrouded blades. While a three-stage design appears to offer superior efficiency, the additional cooling air required to support the added stage effectively negates any performance advantage.

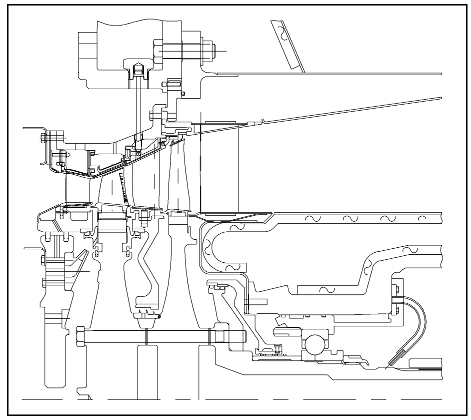
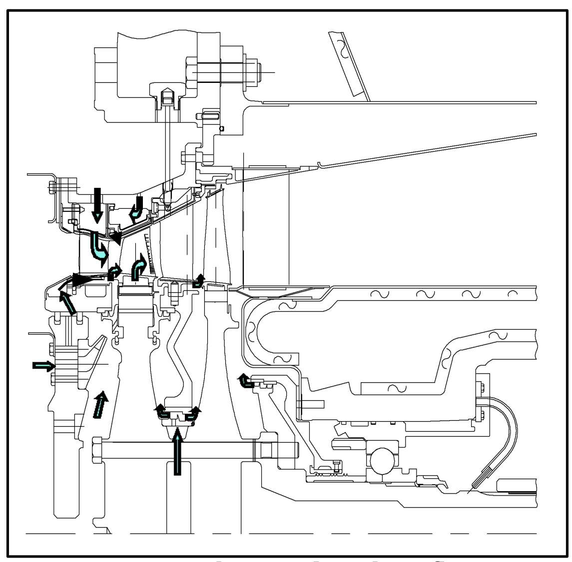


Figure 6 - Mercury 50 turbine

Besides its obvious impacts to cycle efficiency, minimizing the use of cooling air has become increasingly important, as the further pursuit of lean pre-mixed combustion has made cooling air a scarce commodity. Cooling the Mercury 50 (Figure 7) is an even greater challenge due to the fact that 1100°F air from the recuperator is the primary source of cooling. Meeting operating life requirements in this environment has driven advances in both turbine materials and cooling methods. In the *Figure 7 -*



Mercury 50 cooling and sealing flows

case of cooling, two advanced technologies have been applied to the Mercury 50: 1) refined versions of the film and impingement cooling techniques used on our Taurus 70 have been applied to the first-stage nozzle, and 2) a unique leading edge cooling scheme referred to as vortex cooling has been applied to the first-stage blades.

Vortex cooling development has been underway for several years at Solar and involves the use of swirled cooling flow to the leading edge cooling circuit, (Figure 8), greatly improving the heat transfer effectiveness for this portion of the blade for a given amount of cooling air. One of the key technical challenges presented by vortex cooling is in the area of manufacturing. A series of small rectangular slots cast into the blade cooling circuit generates the vortex flow through the leading edge. These openings are smaller than any yet cast into our blades, which presents some unique challenges in the fabrication of this part.

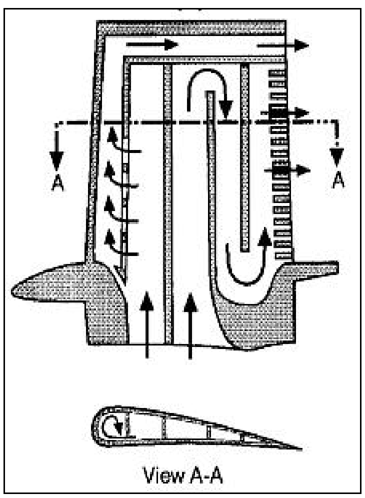


Figure 8 - Vortex Cooling

Vortex cooling offers significant growth potential in terms of cooling effectiveness without incurring the performance penalties associated with showerhead cooling which would otherwise be required in this high temperature application.

The materials used in the manufacture of the Mercury 50 turbine (Figure 9) are a key element in the durability equation

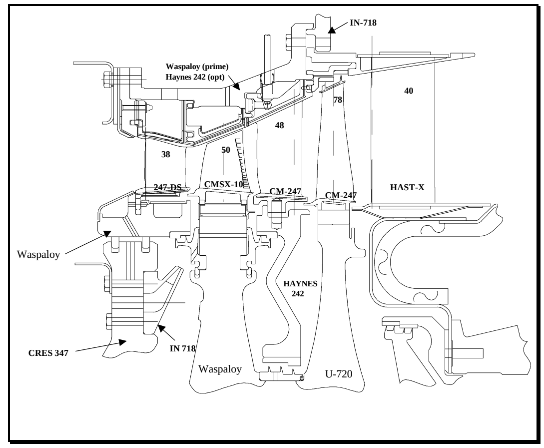


Figure 9 - Mercury 50 Turbine Materials

and represent a mix of current turbine materials as well as next-generation alloys that are relatively new to industrial turbines. The film-cooled first-stage nozzles are constructed from directionally solidified MAR-M-247, while the un-cooled second-stage vanes are constructed from an equiaxed version of the same material. In the case of the unshrouded first-stage blades, a second generation single crystal alloy, Cannon-Muskegon's CMSX-10 has been selected for use. These blades will be mounted to a Waspaloy disk using a version of Solar's traditional fir tree design for blade retention, modified to allow for improved disk-post cooling.

The second-stage blades are of a shrouded design, a first for Solar and are also manufactured from equiaxed MAR-M-247. The shrouded design was chosen due to its superior performance in terms of reduced tip leakage and the improved aerodynamics that derive from the increased aspect ratio of the blades. The lack of cooling for the second stage blades has driven a unique set of requirements for the second stage disk, for which current materials have insufficient material properties. A powdered metal forging of Udimet 720 has been selected for use. The fine grain structure of the rim makes it suitable for the higher rim operating temperatures of the Mercury 50 while still maintaining sufficient low-cycle fatigue strength at the hub.

Rotor Design

While a two-bearing design offers superior cost advantages, it comes at the expense of rotor stability. A three-bearing, single-shaft rotor design (Figure 10) has been selected for its benefits in terms of dynamic performance and stability in transient operating conditions

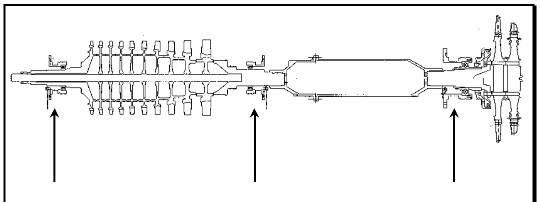


Figure 10 - Mercury 50 rotor bearings location

such as hot restarts and emergency shutdowns from full load. The bearing arrangement incorporates viscous damped rolling element bearings in lieu of hydrodynamic bearings in order to reduce the sizes, and therefore the cost, of the oil sump, pumps, coolers and associated piping. The system employs two radial bearings in the compressor section and a hydraulic damping system designed by Solar for the Mercury application. The damping system is fed from the bearing oil supply and mitigates dynamic transients during operation. The thrust bearing, a damped rolling element bearing, is located downstream of the second-stage turbine rotor. The turbine rotors are overhung to minimize the distance between bearings and to allow the thrust bearing to be located in a cooler environment.

Combustor

Whereas improvements to the basic engine technology have proceeded at an incremental pace over the past decade, improvements in the area of combustion have progressed by leaps and bounds. This has been fueled by both the relentless push by regulators for progressively lower emissions and the emergence of dry emission controls technologies as key product differentiators in an increasingly competitive marketplace. Yet many installations in attainment or non-regulated areas have no need for the additional cost and complexity that accompany low emissions combustion systems. Even so, the industry trend to standardize on low emissions technology to minimize the proliferation of configurations is sweeping many such customers along for the ride.

There are almost as many approaches to dry emissions control as there are manufacturers, though two technologies have attracted the bulk of the attention: 1) lean pre-mixed combustion, and 2) catalytic combustion. The mechanical configurations associated with each are distinctly different and lend themselves to different design approaches within the gas turbine. As will be described later, the design of the Mercury 50 combustor will readily accommodate either technology such that it can be tailored to the needs of the particular installation.

Ultra-Lean Premixed Combustion - The Mercury 50's ultra-lean pre-mixed design is a further refinement of Solar's successful SoLoNOx™ technology. The Mercury 50 design incorporates eight ultra-lean pre-mixed injectors, a backside-cooled annular combustor liner and closed-loop carbon monoxide (CO) feedback control to achieve single-digit NOx emissions across the 50-100 percent load range (Figure 11).

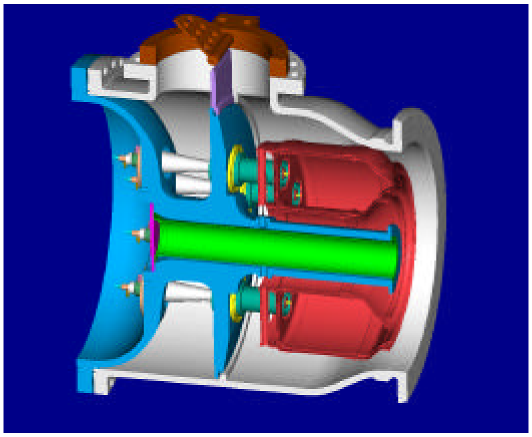


Figure 11 - Mercury 50 Combustion System

Refinement of the lean pre-mixed concept developed for the SoLoNOx product line to support single-digit NOx emissions requires the use of additional dilution air through the injector body to reduce primary zone. The use of variable geometry effectively modulates airflow through the injectors as a function of load to maintain consistent primary zone temperatures. However, the pressure drop across the combustor increases significantly at lower loads as excess dilution air is bypassed around the injector. Bleeding air from the combustor case at lower power settings can mitigate this, but at the expense of part-load efficiency. The compensating nature of the Mercury 50's variable geometry design is such that the pressure drop across the combustor remains relatively constant, allowing lean operation across a wide load range without the need for compressor bleed at intermediate loads.

The scarcity of cooling air and the effects of combustor liner cooling on the formation of CO during the combustion process have brought about a change in the way the Mercury 50 combustor liner is cooled. As primary zone temperatures are reduced to support single digit NOx combustion, CO levels tend to rise, particularly in the vicinity of the relatively cool liner walls, where the CO to CO_2 reaction is quenched. Minimizing both drives a balance between higher temperatures for reduced CO and lower temperatures for reduced NOx.

The Mercury 50's alternative liner cooling scheme, referred to as Augmented Backside Cooling (ABC), maintains higher wall temperatures as compared to louver or effusion cooling techniques to further retard the formation of CO during the combustion process. This in turn allows the reduced primary zone temperatures necessary for single digit NOx without sacrificing an increase in CO emissions.

The combustor liner is protected by a ceramic Thermal Barrier Coating (TBC) that is plasma sprayed to the metallic substrate. The addition of trip strips to the back-side of the liner serve to break up the boundary layer and promote improved heat transfer. Liners manufactured from continuous fiber-reinforced ceramic composites (CFCC), a design being developed on our Ceramic Stationary Gas Turbine (CSGT) program, are also being considered for use in the Mercury application as this technology matures.

Improvements in mixedness and minimization of combustor oscillations are key design improvements that have been incorporated into the Mercury 50 dual fuel injectors (Figure 12). The use of airfoil main air swirlers with integral gas injection at the upstream edges serves to improve the premixing to promote lean combustion while preventing flashback. In the liquid mode, the use of air atomization during light-off and air cooling of the tip have been added as refinements to the basic design.

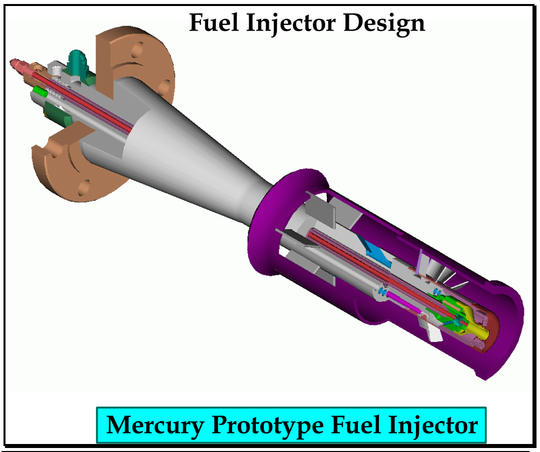


Figure 12. Mercury 50 Fuel Injector

Reliably maintaining single-digit emissions performance across a wide range of loads and operating conditions has necessitated the incorporation of closed-loop controls. A CO sensor has been added to the turbine exhaust and is used to drive a proportional control loop that continually adjusts compressor inlet guide vanes (IGV), the air diverter valve and the fuel control to accurately control the level of CO (and hence NOx) formation during engine operation.

Catalytic Combustion System - The design of the catalytic combustion system follows more than four years of development work during which Solar and our partner Catalytica refined and rig tested the basic design of the catalyst beds (Figure 13) to prove their suitability for use in a gas turbine application. Air and fuel are thoroughly mixed and allowed to partially react in the catalyst bed, where temperatures are kept sufficiently low to avoid damage to the substrate and supporting structure. Burnout is completed downstream of the catalyst bed, where temperatures are sufficiently low to avoid NOx formation.

The 900°F inlet temperature required to initiate the catalytic reduction of the fuel normally requires the use of a preburner, which is essentially a small version of a

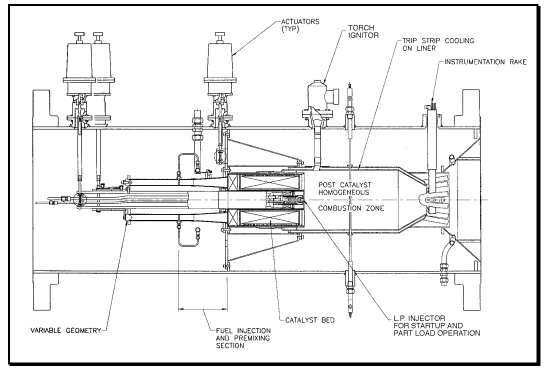


Figure 13 - Full Scale Catalyst Test Rig

SoLoNOx injector upstream of the catalyst. One of the many advantages offered by the Mercury 50's recuperated cycle is that the combustor inlet air is maintained at approximately 1100°F, thus eliminating the need for preburners, the major source of what little NOx is produced by catalytic combustion systems. The system uses five nine inch catalyst cans (Figure 14) and again utilizes the same compensating geometry to maintain a consistent equivalence ratio across the 50-100 percent operating range. A cooled can-to-annular transition piece is used to channel the combustor discharge to the first-stage turbine nozzles. Provisions have been made to accommodate rapid changeout of the catalyst beds as required with a minimum of downtime.

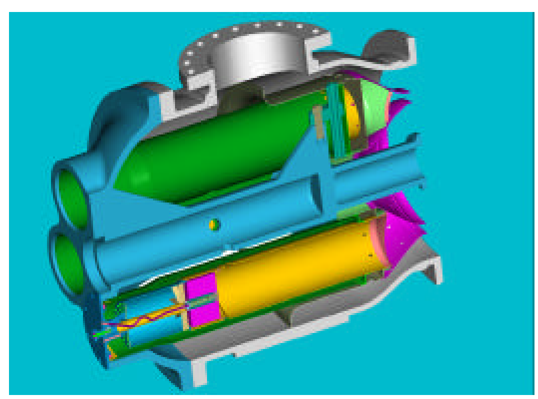


Figure 14 - Catalytic Combustor System

Package Design

The more traditional method of introducing improvements to industrial gas turbine systems has been limited to the gas turbine itself and has typically taken the form of incremental improvements to existing technologies that offer marginal improvements to firing temperatures, pressure ratios or cooling efficiencies. Unfortunately, this approach has failed to capitalize on improvements that can be realized in the other areas of the gas turbine system. Specifically, the layout of the turbine in concert with the package have a significant impact on the cost, efficiency, reliability and maintainability of the gas turbine system.

In the case of a typical package, ancillary systems consume nearly 8% of the useful power of the machine (Figure 15) and provide an excellent opportunity for improvement.

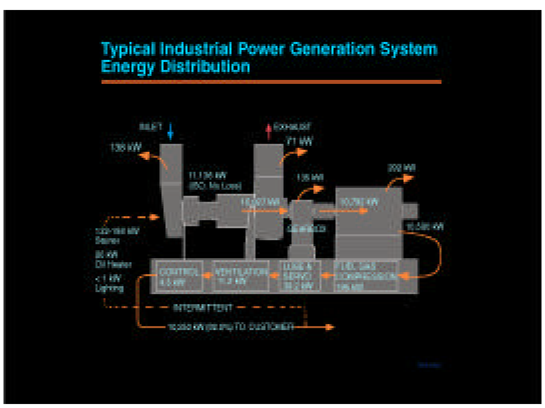


Figure 15 – System Parasitic Losses

As a consequence, Solar's approach to the design of our ATS has been heavily focused at the system level. Examples of this have been the use of variable-frequency AC drive motors for such things as lube oil pumps and cooling fans, where the power output can be tailored to meet the actual load requirements. Extensive use of advanced analytical design tools such as Computational Fluid Dynamics (CFD) combined with advanced aero codes and the use of vortex generators in the exhaust casing to improve pressure recovery have contributed towards significant reductions in exhaust and inlet losses.

Advanced design and modeling techniques have also been applied to the gearbox design. The use of double helical gearing in our epicyclic gearbox, an approach typically reserved for much larger applications, has eliminated the need for thrust bearings and improved the component efficiency in the process. And finally, in concert with our generator suppliers, we are also applying technologies typically reserved for use in much larger generators to achieve similar improvements in component efficiencies. The use of profiled conductors for the stator windings and thin layer laminates made from advanced materials are two key contributors to this achievement.

General Layout

One of the most significant Mercury 50 innovations is the layout of the core engine, around which the package has been synergistically designed. The resulting design offers significant advantages in terms of cost, performance and maintainability.

Combustor Flexibility - The need to accommodate multiple combustion systems has been a major factor in the design of the Mercury 50. Locating the combustion system between the turbine and compressor as past convention has dictated limits the ability to make changes without incurring major impacts to other subsystems. The centerline design fixes the length of the combustor and the compressor and turbine cases define the mating interfaces. This has led us to adopt a unique engine layout that will accommodate either the ULP or catalytic combustion systems interchangeably and represents a new innovation in the design of industrial gas turbines. The combustor case and diverter valve assembly are common to both systems, while the end cover, liners, injectors and manifolding are unique to each combustion system.

Simplified Flow Path - The complex flow path of the recuperated cycle also provided design challenges that were effectively addressed in the layout. The recuperator is supplied with air from the compressor discharge plenum on one end, while heated air is collected at the other end and supplied to the combustor. Turbine exhaust is collected at the bottom center of the recuperator and discharged from the top. On a conventional turbine, this flow path requires a somewhat complex series of piping, elbows, flanges, bellows and pipe hangers.

But by altering the arrangement of the components themselves, a graceful flow path (Figure 16) can be accommodated that naturally follows the flow of the recuperator.

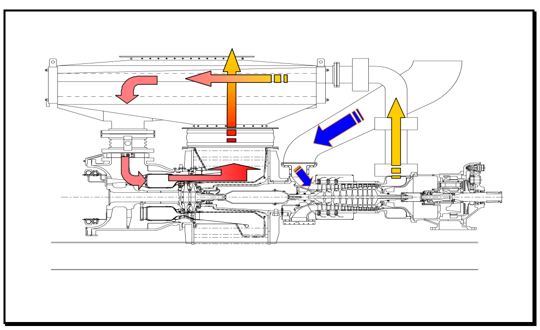


Figure 16 - Mercury 50 Flow Path

Compressor discharge is at the end of the machine in the same plane as the inlet header to the recuperator. The inlet to the combustor is located at the end of the machine in the same plane as the recuperator discharge header. Finally, the turbine exhausts at the center of the engine and discharges up through the recuperator. In essence, the layouts of the compressor and turbine have been reversed to accommodate a greatly simplified flow path.

A uniquely designed component referred to as the centerframe is used to interconnect the turbine and compressor sections in lieu of the hot strut designs typically used by gas turbines (Figure 17). As the load carrying members of the centerframe are located in a cool environment external to the turbine flow path, axial movement of the turbine case due to thermal growth is minimized, enabling tight tip clearances to be effectively maintained.

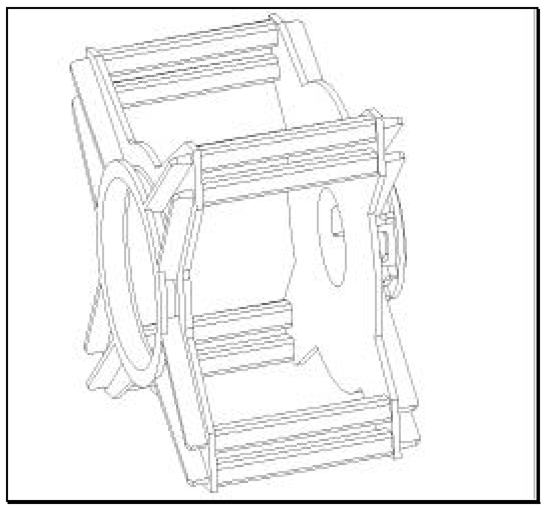


Figure 17 - Mercury 50 Centerframe

Modular Assembly and Maintenance - Another factor in the design of the package was the desire for modularity in which each of the major subsystems, including the combustor, turbine, compressor, recuperator, gearbox and generator. Each can be changed independently in the field in a single shift without the need to replace the entire engine (Figure 18). The ability to replace entire modules can also limit the amount of on-site troubleshooting required because the module can be replaced and repaired off-line.

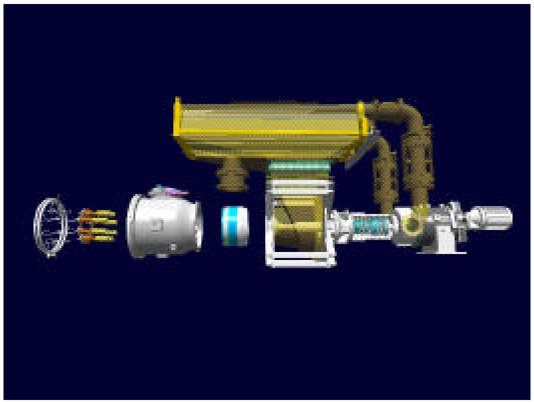


Figure 18 - Mercury 50 Modular Design

Changeout of modules and major components is accommodated as follows:

Liner/injector changeout - Injectors and ignitors can be unbolted and withdrawn from the end cover for individual servicing as required. In addition, the combustor end cover can be unbolted, removed and withdrawn from the case to provide direct access to the combustor liners, injectors, ignitors and manifolding. These components can be serviced individually or replaced as an entire assembly as required.

First-stage turbine nozzle - The entire combustor assembly can be unbolted and withdrawn to provide clear access to the first-stage turbine nozzles for replacement without disturbing the remainder of the turbine.

Turbine assembly and thrust bearing - The turbine shaft coupling is unbolted from the compressor via an access port in the engine centerframe. Then following removal of the combustor assembly as previously described, the turbine assembly is unbolted from the engine centerframe and withdrawn and replaced as a unit.

Compressor assembly - The turbine shaft coupling is disconnected as previously described and the compressor is unbolted from the engine centerframe. The compressor can then be withdrawn and replaced as a unit.

Gearbox and Generator - Unbolting the couplings for these units allows them to be individually removed from the package and replaced without disturbing the other components.

Designing the Mercury 50 from the centerline out to synergistically incorporate flexibility, modularity, maintainability and low cost into the turbine system is central to its ability to meet the key product goals stated at the beginning of the program:

- Efficiency
- Environmental Performance
- Fuel Flexibility
- Cost of Power
- Reliability and Maintainability

Summary

The demand for low-cost, reliable power has increased dramatically in recent years. When combined with the emergence of markets such as distributed generation, excellent growth opportunities exist for power generation products that can effectively meet the varied goals of this diverse customer base. With this increased demand, the industry has seen a push towards power generation equipment in smaller sizes in a wide variety of applications. This size range has long been dominated by reciprocating engines, where their low first cost and high efficiency vs. small industrial turbines has given them an advantage in applications where footprint, emissions and maintenance are not key issues. However, the emerging societal trends are pushing towards progressively lower emissions, fuel flexibility and unobtrusive installations in non-industrial locations. Large domestic reserves of clean-burning natural gas has made this the fuel of choice in many applications. And the need to cleanly burn a wide variety of fuels of opportunity, such as digester gas, landfill gases, refinery by-products, etc. has placed ever increasing importance on the design of combustion systems. Together these marketplace trends are tipping the scales in favor of industrial turbines for many applications.

The Mercury 50 has been designed to offer superior performance and operating flexibility at a price that is competitive with alternative power generating technologies. Scaled to different sizes as is currently envisioned, the Mercury 50 family of turbines is capable of satisfying the needs of a wide array of users in a number of different applications. It represents a balanced approach to the tradeoff between the benefits of new technology, low cost and high reliability that is targeted directly at the needs of the industrial power generation marketplace.

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